

Generalized Parton Distributions in light meson production.

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Abstract

We analyze light meson electroproduction within the handbag model, where the amplitude factorizes into Generalized Parton Distributions (GPDs) and a hard scattering part. The cross sections and spin asymmetries for various vector and pseudoscalar mesons are analyzed. We discuss what information on hadron structure can be obtained from GPDs.

1 Introduction

In this report, we study lepton production of light mesons at small momentum transfer and large photon virtualities Q^2 on the basis of the handbag approach. In this kinematic region the leading twist amplitude factorizes into a hard meson electroproduction subprocess off partons and GPDs [1]. The hard subprocess is calculated within the modified perturbative approach (MPA) where quark transverse degrees of freedom accompanied by Sudakov suppressions are considered. The quark transverse momentum regularizes the end-point singularities in the higher twist amplitudes so that it can be calculated in the model. The GPDs which contains information on the soft physics are constructed using double distributions. They depend on \bar{x} -the momentum fraction of the parton, ξ - skewness which is determined as a difference of the parton momenta and related to Bjorken- x_B as $\xi \sim x_B/2$ and t -momentum transfer.

Within our approach [2–4] we calculate the gluon and valence quark GPDs H contribution to the meson production amplitudes and, subsequently, the cross sections and the spin observables in the light meson electroproduction off unpolarized proton target. Using GPDs E we extend our analysis to a transversally polarized target. We calculate cross sections and the A_{UT} asymmetry for various vector meson productions. Our results [2–5] on meson electroproduction are in good agreement with experimental data in the HERA [6, 7] COMPASS [8] and HERMES [9] energy range.

The study of pseudoscalar meson electroproduction [10, 11] gives access to the GPD \tilde{H} and \tilde{E} . In the description of this reaction the twist-3 effects are very essential too. Within the handbag approach these twist-3 effects were modeled by the transversity GPDs, in particular, H_T and E_T in conjunction with the twist-3 pion wave function. Our results [10, 11] on the cross section and moments of spin asymmetries for the polarized target are in good agreement with HERMES experimental data.

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2 GPDs and mesons production amplitudes in the handbag approach

In the handbag model, the amplitude of the vector meson production off the proton with positive helicity reads as a convolution of the hard partonic subprocess \mathcal{H}^a and GPDs $H^a(\tilde{H}^a)$

$$\mathcal{M}_{\mu'\pm,\mu+}^a = \sum_a [\langle H^a \rangle + O(\langle \tilde{H}^a \rangle)] \quad (1)$$

$$\langle H^a \rangle = \sum_{\lambda} \int_{xi}^1 d\bar{x} \mathcal{H}_{\mu'\lambda,\mu\lambda}^a(Q^2, \bar{x}, \xi, t) \hat{H}^a(\bar{x}, \xi, t),$$

where a denotes the gluon and quark contribution with the corresponding flavors; μ (μ') is the helicity of the photon (meson), and \bar{x} is the momentum fraction of the parton with helicity λ . In the region of small $\bar{x} \leq 0.01$ gluons give the dominant contribution. At larger $\bar{x} \sim 0.1$ the quark contribution plays an important role [3].

The subprocess amplitude is calculated within the MPA [12]. The amplitude \mathcal{H}^a is a contraction of the hard part \mathcal{F}^a , which is calculated perturbatively and includes the transverse quark momentum \mathbf{k}_{\perp} , and the nonperturbative \mathbf{k}_{\perp} -dependent meson wave function [13]. The gluonic corrections are treated in the form of the Sudakov factors in the hard partonic subprocess \mathcal{H}^a . The resummation and exponentiation of the Sudakov corrections can be done in the impact parameter space [12]. We use the Fourier transformation to transfer integrals from the \mathbf{k}_{\perp} to \mathbf{b} space. Within the MPA the subprocess amplitude in the impact parameter (\mathbf{b}) space reads

$$\begin{aligned} \mathcal{H}_{\mu'\lambda,\mu\lambda}^a = \int d\tau d^2b \hat{\Psi}(\tau, -\mathbf{b}, \mu_F) \hat{\mathcal{F}}_{\mu'\lambda,\mu\lambda}^a(\bar{x}, \xi, \tau, Q^2, \mathbf{b}, \mu_R) \alpha_s(\mu_R) \\ \times \exp[-S(\tau, \mathbf{b}, Q^2, \mu_F, \mu_R)]. \end{aligned} \quad (2)$$

The Sudakov factor S and the choice of the renormalization (μ_R) and factorization (μ_F) scales can be found in [2, 3]. The hard scattering kernels \mathcal{F} and $\hat{\Psi}(\tau, -\mathbf{b})$ in (2) are the Fourier transform of the \mathbf{k}_{\perp} dependent subprocess amplitude, and the meson wave function (τ ($1 - \tau$) is the momentum fraction of the quark (antiquark) that enters into the meson, defined with respect to the meson momentum).

The \hat{H}^a in (1) is expressed in terms of GPDs which contain the extensive information on the hadron structure. At zero skewness and momentum transfer GPD becomes equal to the corresponding parton distribution function(PDF). The form factors of hadrons are the first moments of the corresponding GPDs,

$$\begin{aligned} \int dx H^a(x, \xi, t) &= F_1^a(t); \\ \int dx E^a(x, \xi, t) &= F_2^a(t), \end{aligned} \quad (3)$$

where F_1^a and F_2^a are the Dirac and Pauli form factors with flavor a . Information on the parton angular momenta can be obtained from the Ji sum rules [14]

$$J^q = \frac{1}{2} \int dx x (H^q(x, \xi, 0) + E^q(x, \xi, 0)). \quad (4)$$

To estimate GPDs, we use the double distribution (DD) representation [15]

$$H_i(\bar{x}, \xi, t) = \int_{-1}^1 d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(\beta + \xi \alpha - \bar{x}) f_i(\beta, \alpha, t) \quad (5)$$

which connects GPDs with PDFs through the DD function f ,

$$f_i(\beta, \alpha, t) = h_i(\beta, t) \frac{\Gamma(2n_i + 2)}{2^{2n_i+1} \Gamma^2(n_i + 1)} \frac{[(1 - |\beta|)^2 - \alpha^2]^{n_i}}{(1 - |\beta|)^{2n_i+1}}. \quad (6)$$

The functions h_i are expressed in terms of PDFs and parameterized as

$$h(\beta, t) = N e^{b_0 t} \beta^{-\alpha(t)} (1 - \beta)^n. \quad (7)$$

Here the t -dependence is considered in a Regge form and $\alpha(t)$ is a corresponding Regge trajectory.

From different meson productions at moderate HERMES and COMPASS energies we can get information about valence and sea quark effects. Really, the quarks contribute to meson production processes in different combinations. For uncharged meson production we have standard GPDs and find

$$\rho : \propto \frac{2}{3} H^u + \frac{1}{3} H^d; \quad \omega : \propto \frac{2}{3} H^u - \frac{1}{3} H^d. \quad (8)$$

For production of charged and strange mesons we have transition $p \rightarrow n$ and $p \rightarrow \Sigma$ GPDs and we have

$$\rho^+ : \propto H^u - H^d; \quad K^{*0} : \propto H^d - H^s. \quad (9)$$

For pseudoscalar mesons the polarized GPDs contribute as

$$\pi^+ : \propto \tilde{H}^u - \tilde{H}^d; \quad \pi^0 : \propto \frac{2}{3} \tilde{H}^u + \frac{1}{3} \tilde{H}^d. \quad (10)$$

The same combinations are valid for E, \tilde{E} contributions. Thus, we can test various GPDs in the mentioned reactions.

3 Vector meson electroproduction

In this section, we study vector meson electroproduction and consider the cross section and spin observables using amplitudes and GPDs calculated in the previous section. The H GPDs are modeled by DD (5),(6). The parameters in (7) are determined from the CTEQ6 analysis of PDFs [16]. More details together with parameters of the model can be found in [2–4].

Our approach has been used to analyze data on ρ^0 and ϕ electroproduction in a wide energy range. We consider the gluon, sea and quark GPD H contribution to the meson production amplitudes. This permits us to study vector meson production from moderate HERMES energies $W \sim 5\text{GeV}$ till high HERA energies $W \sim 75\text{GeV}$ [3, 4]. The k_\perp^2/Q^2 corrections in propagators of the hard subprocess amplitudes are extremely important at low Q^2 and permit us to describe experimental data properly. If we omit k_\perp^2/Q^2

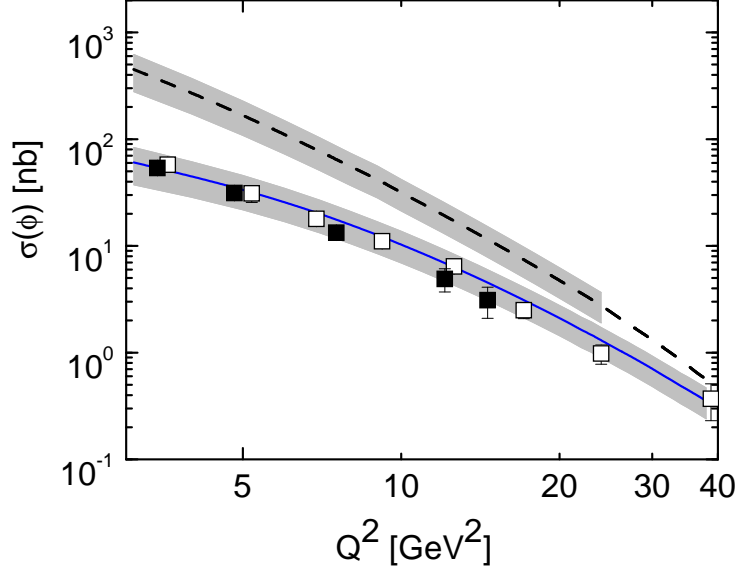


Figure 1: Longitudinal cross sections of ϕ production at $W = 75\text{GeV}$. Data are from H1 -solid symbols and ZEUS -open symbols. Dashed line - leading twist result.

corrections (leading twist approximation), the cross section increases by a factor of about 10 at $Q^2 \sim 3\text{GeV}^2$ (see Fig. 1).

The obtained results [3,4] are in good agreement with the experiments at HERA [6,7], COMPASS [8], HERMES [9] and E665 [17] energies for electroproduced ρ and ϕ mesons. If we extend our analysis to lower energies $W \sim 2.5\text{GeV}$, we find a good description of the ϕ cross section at CLAS [18], as shown on Fig. 2. This means that we have good results for gluon and sea quark contributions which are important in the ϕ meson production.

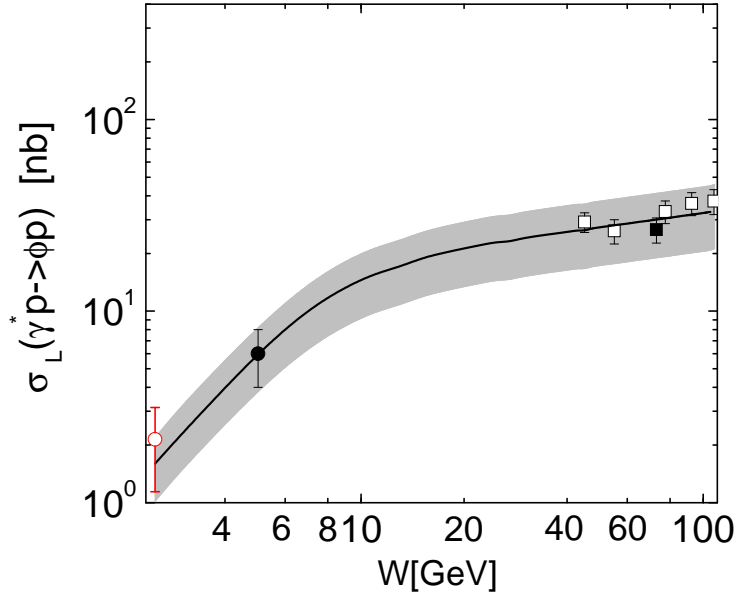


Figure 2: The longitudinal cross section for ϕ at $Q^2 = 3.8\text{GeV}^2$. Data: HERMES (solid circle), ZEUS (open square), H1 (solid square), open circle- CLAS data point

For the ρ production we find an essential contribution of the valence quarks which

are of the order of gluon and sea effects at $W \sim 5\text{GeV}$. At lower energies, the quark contribution decreases, as well as the gluon and sea one. As a result, the cross section falls at energies $W \leq 5\text{GeV}$. This is in contradiction with CLAS [18] results where the rapid growth of σ_ρ is observed in this energy range, Fig. 3. Thus, most probably we have a problem with the valence quark contribution at low JLAB energies, which is not solved till now.

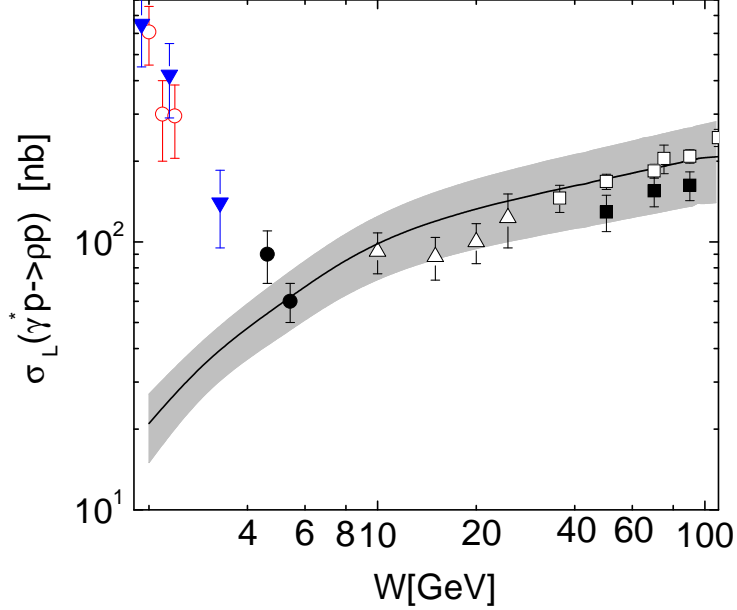


Figure 3: The longitudinal cross section for ρ at $Q^2 = 4.0\text{ GeV}^2$. Data: HERMES (solid circle), ZEUS (open square), H1 (solid square), E665 (open triangle), open circles- CLAS, CORNELL -solid triangle

Using the quarks contribution (8), (9) to meson amplitudes we can calculate the cross section for different meson production. In Fig. 4, our results for COMPASS energy $W = 10\text{GeV}$ are shown.

The proton spin-flip amplitude is associated with E GPDs

$$\mathcal{M}_{\mu'-, \mu+} \propto \frac{\sqrt{-t}}{2m} \int_{-1}^1 d\bar{x} E^a(\bar{x}, \xi, t) F_{\mu', \mu}^a(\bar{x}, \xi). \quad (11)$$

The GPD E is not well known till now. The standard relation

$$E^a(x, 0, 0) = e^a(x) \quad (12)$$

takes place where e^a is the corresponding PDF. We constrained e^a by the Pauli form factors of the nucleon [19], positivity bounds and sum rules. The GPD E is constructed using DD.

We would like to note that the first moment of e is proportional to the quark anomalous magnetic moment

$$\int_0^1 dx e_{val}^a(x) = \kappa^a. \quad (13)$$

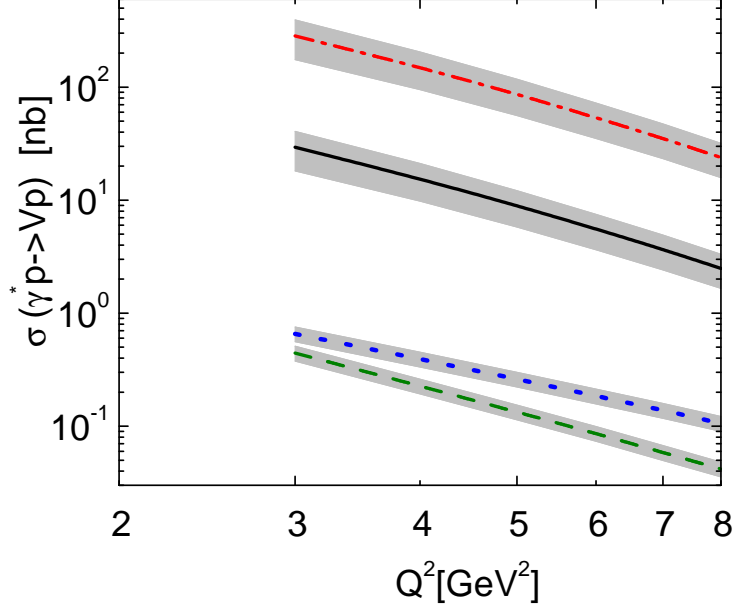


Figure 4: Predicted integrated over t cross section at COMPASS $W = 10\text{GeV}$ energies for various mesons. Dotted-dashed line ρ^0 ; full line ω ; dotted line ρ^+ and dashed line K^{*0} .

The κ^u and κ^d have different signs and we can conclude that the GPDs E^u and E^d have different signs too. From (8) we see that we should have essential compensation of E^u and E^d effects for ρ meson and enhancement of their contributions for ω production.

We calculate the A_{UT} asymmetry for transversally polarized protons in [5]. The asymmetry is sensitive to interferences of the amplitudes determined by the E and H GPDs

$$A_{UT} = \propto \frac{\text{Im} \langle E^* \rangle \langle H \rangle}{|\langle H \rangle|^2}. \quad (14)$$

The GPD H was taken from our analysis of the vector meson electroproduction. Our results for the moments of the A_{UT} asymmetry for the ρ^0 production [5] describe well HERMES data [20]. The predictions for COMPASS on t -dependence of asymmetry at $W = 8\text{GeV}$ shown in Fig. 5 are in good agreement with preliminary COMPASS data [21]. Due to essential compensation of the GPD E for valence quark, the A_{UT} asymmetry for ρ^0 is predicted to be quite small.

The predictions for the A_{UT} asymmetry at $W = 5\text{GeV}$ and $W = 10\text{GeV}$ were given for the ω , ρ^+ , K^{*0} mesons [5]. It was mentioned that E^u and E^d GPD contributions have the same sign in the ω production amplitude, and our results for A_{UT} asymmetry at HERMES and COMPASS energies are negative and not small [5].

Predicted ρ^+ asymmetry is positive and rather large $\sim 40\%$ Fig. 6. However, smallness of the cross section in Fig. 4 does not give a good chance to measure this asymmetry.

In our model we found not small angular momenta for u quarks and gluons [5]

$$\langle J_v^u \rangle = 0.222, \quad \langle J_v^d \rangle = -0.015, \quad \langle J^g \rangle = 0.214, \quad (15)$$

which are not far from the lattice results.

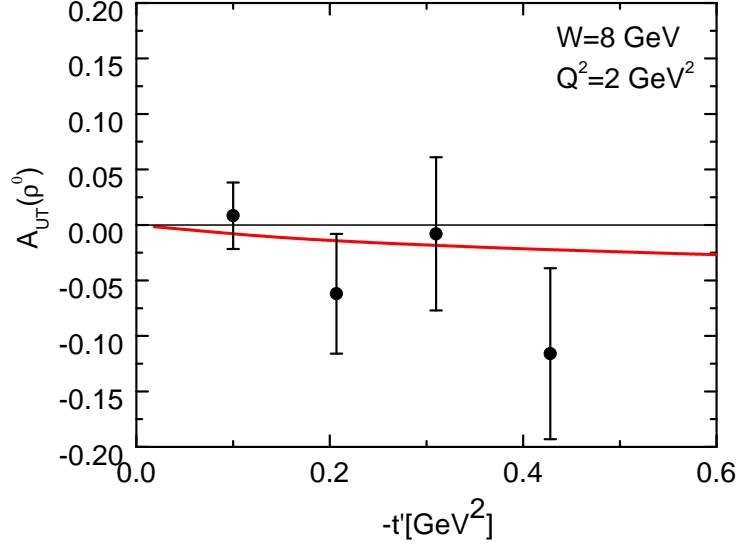


Figure 5: Predicted A_{UT} asymmetry of the ρ^0 production at COMPASS with COMPASS data.

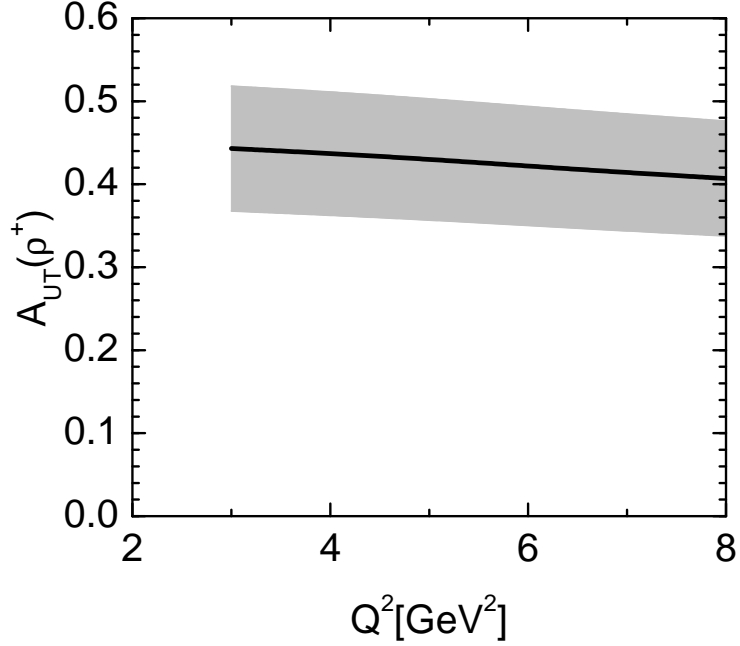


Figure 6: Predicted A_{UT} asymmetry of the ρ^+ production at HERMES.

4 Electroproduction of pseudoscalar mesons

The amplitude of the pseudoscalar meson production with longitudinally polarized photons $\mathcal{M}_{0\nu',0\nu}^P$ dominates in the process and is determined in terms of polarized \tilde{H} GPDs. It can be written at large Q^2 [10] as

$$\mathcal{M}_{0+,0+}^P \propto \sqrt{1-\xi^2} [\langle \tilde{H}^P \rangle - \frac{2\xi m Q^2}{1-\xi^2} \frac{\rho_P}{t-m_P^2}];$$

$$\mathcal{M}_{0-,0+}^P \propto \frac{\sqrt{-t'}}{2m} \left[\xi \langle \tilde{E}^P \rangle + 2mQ^2 \frac{\rho_P}{t - m_P^2} \right]. \quad (16)$$

The first terms in (16) represent the handbag contribution to the pseudoscalar (P) meson production which is calculated within the MPA with the corresponding transition GPDs in (1). For the π^+ production we have the $p \rightarrow n$ transition GPD where the isovector combination contributes $\tilde{F}^{(3)} = \tilde{F}^{(u)} - \tilde{F}^{(d)}$.

The second terms in (16) appear for charged meson production and are connected with the P pole contribution, where we use the fully experimentally measured electromagnetic form factor of P meson. The amplitudes with transversely polarized photons are suppressed as $1/Q$ and can be found in [10].

Using (16) we calculate all amplitudes with the exception of $\mathcal{M}_{0-,++}$ and $\mathcal{M}_{0+,++}$. It can be shown from the angular momentum conservation that we have the following rule:

$$M_{\mu'\nu',\mu\nu} \propto \sqrt{-t'}^{|\mu-\nu-\mu'+\nu'|} \quad (17)$$

and the amplitude $\mathcal{M}_{0-,++}$ should be constant at small t' . However, this amplitude calculated in the handbag approach behaves as $-t'$ at small momentum transfer. This problem can be solved if a twist-3 contribution to the amplitude $\mathcal{M}_{0-,++}$ is considered. Within the handbag approach this twist-3 effect can be modeled by the transversity GPDs, in particular H_T , in conjunction with the twist-3 pion wave function

$$\mathcal{M}_{0-, \mu+}^{P, twist-3} \propto \int_{-1}^1 d\bar{x} \mathcal{H}_{0-, \mu+}(\bar{x}, \dots) [H_T^P + \dots O(\xi^2 E_T^P)]. \quad (18)$$

For details of calculation of the $\mathcal{H}_{0-, \mu+}$ amplitudes see [10].

The GPD H_T is calculated using DD form. The transversity PDFs are connected with H_T as

$$H_T^a(x, 0, 0) = \delta^a(x), \quad (19)$$

the PDF δ is parameterized on the basis of the model [23]

$$\begin{aligned} \delta^a(x) &= C N_T^a x^{1/2} (1-x) [q_a(x) + \Delta q_a(x)]; \\ N_T^u &= 0.78, \quad N_T^d = -1.0. \end{aligned} \quad (20)$$

It was found that H_T contributions are essential in the description of the polarized π meson production [10].

We consider now the role of the $\mathcal{M}_{0+,++}$ amplitude which is important in some asymmetries and cross section like σ_T , σ_{TT} . This amplitude is equal to zero in the leading twist approximation. The twist-3 contribution to the amplitude [11] has a form similar to (18)

$$\mathcal{M}_{0+, \mu+}^{P, twist-3} \propto \frac{\sqrt{-t'}}{4m} \int_{-1}^1 d\bar{x} \mathcal{H}_{0-, \mu+}(\bar{x}, \dots) \bar{E}_T^P \quad (21)$$

where

$$\bar{E}_T^P = 2 \tilde{H}_T + E_T. \quad (22)$$

Unfortunately, the information on E_T was obtained only in the lattice QCD [24]. It was found that the lower moments of E_T for u and d quarks are large, have the same

sign and a similar size. This means that we have an essential compensation for π^+ where the combination $E_T^{(3)} = E_T^u - E_T^d$ contributes. The parameters for individual PDFs were taken from the lattice results [24] for E_T moments. The DD model was used to estimate E_T .

The obtained results on the cross section and moments of spin asymmetries [10] for the polarized target are in good agreement with HERMES [22] experimental data.

In Fig. 7, we show the full cross section of the π^+ production at HERMES with result for zero E_T . The model describes fine HERMES data, and the E_T contribution is negligible. The main contribution to the cross section is determined by the leading-twist longitudinal amplitude.

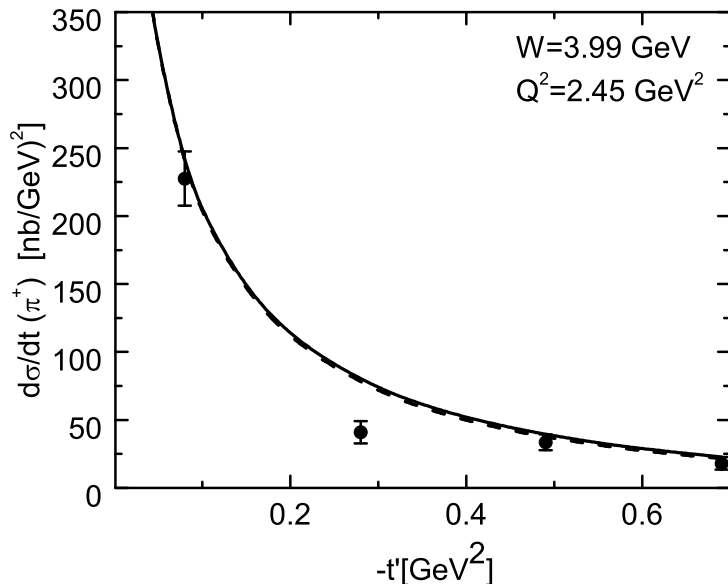


Figure 7: The cross section of the π^+ production with HERMES data. Dashed line -for $E_T = 0$

The transversity effects are essential in the asymmetry of the π^+ production. In Fig. 8, we show our results for the $\sin(\phi - \phi_s)$ moment of A_{UT} asymmetry with and without the E_T contribution. It can be seen that E_T effects are very important and improve the description of asymmetry.

Similar transversity effect is visible in the A_{UL} asymmetry of the π^+ production, Fig. 9. Other asymmetries are described well too in the model [10].

Now we shall discuss our results for the π^0 production where a large E_T contribution is expected. Really, for this reaction we find $E_T^0 = 2/3 E_T^u + 1/3 E_T^d$ and we have enhancement of E_T effects in the π^0 production instead of compensation for π^+ . In Fig. 10 we present our results [11] for the cross section of the π^0 production at HERMES energies. The longitudinal cross section, which is determined mainly by the leading twist contribution and expected to play an essential role, is much smaller with respect to the $d\sigma_T/dt$ cross section where the twist-3 E_T contribution is important. Thus, we observe the predominated role of transversally polarized photons which are mainly generated by E_T . Of course, this effect will disappear at large Q^2 because twist-3 effects have $1/Q$ suppression with respect to the leading twist contribution.

In Fig. 11, we show the energy dependence of the π^0 cross section at fixed Q^2 [11].

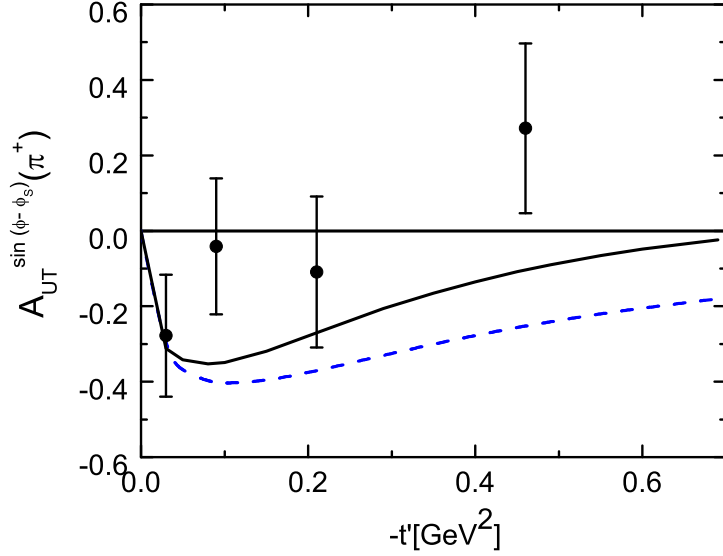


Figure 8: The $\sin(\phi - \phi_s)$ moment of A_{UT} asymmetry of the π^+ production with HERMES data. Dashed line - for $E_T = 0$

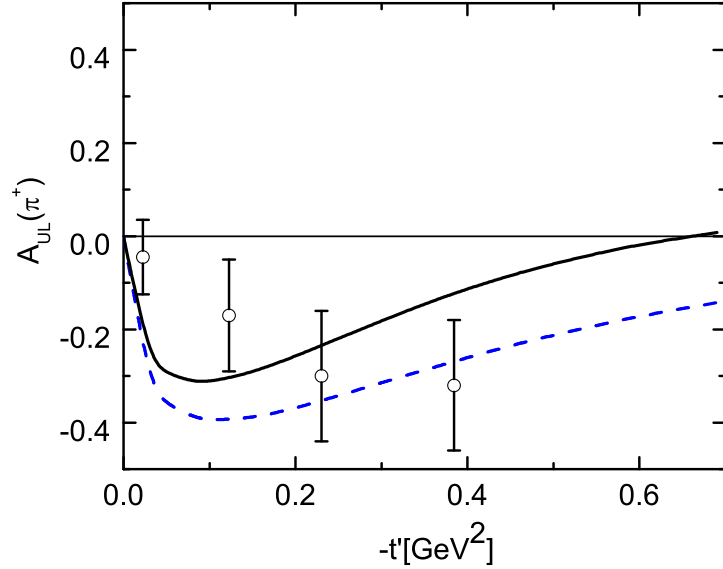


Figure 9: A_{UL} asymmetry of the π^+ production with HERMES data. Dashed line -for $E_T = 0$

In the COMPASS energy range the cross section is not small and can be measured. In Fig. 12, our results for the $\sin(\phi - \phi_s)$ and $\sin \phi_s$ moments of A_{UT} asymmetries at HERMES energy are presented which are predicted to be not small.

5 Conclusion and Summary

In this report, we have studied the light meson electroproduction within the handbag approach. The production amplitude at large Q^2 factorizes into the hard subprocess and GPDs. The MPA was used to calculate the hard subprocess amplitude, where the

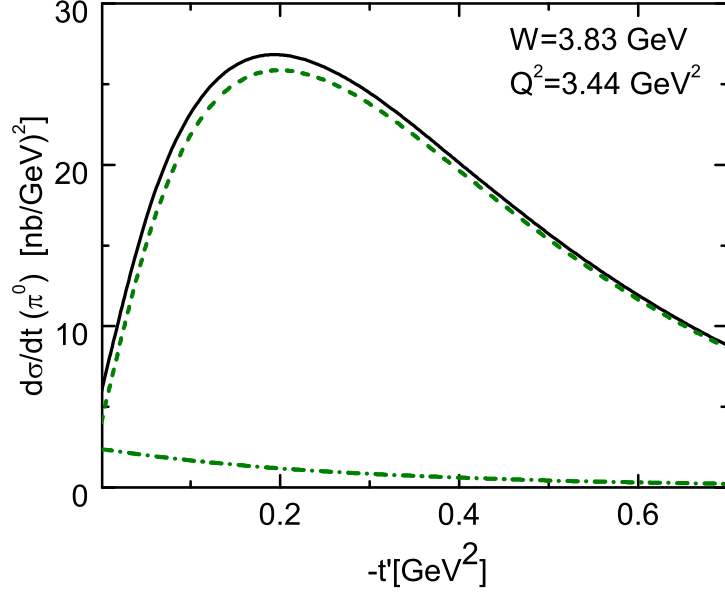


Figure 10: The cross section of the π^0 production at HERMES. Full line-full cross section; dashed-dotted- $d\sigma_L/dt$, dotted line- $d\sigma_T/dt$.

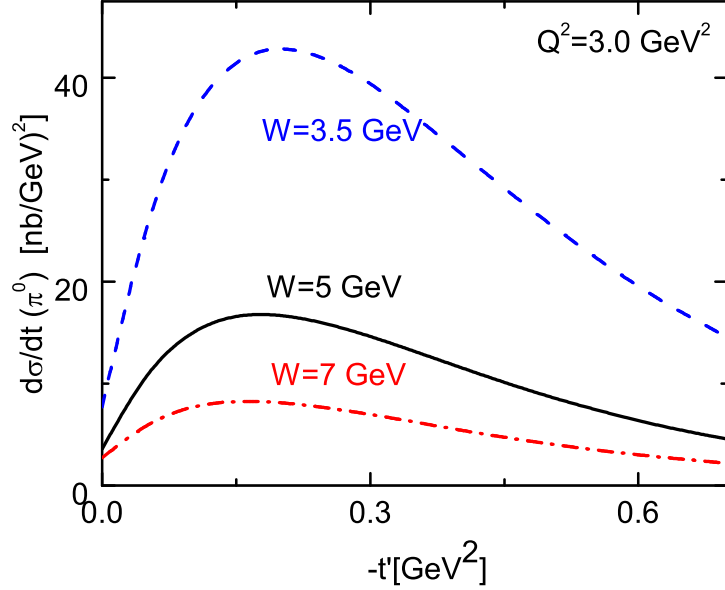


Figure 11: Energy dependence of the cross section of the π^0 production at $Q^2 = 3\text{GeV}^2$

transverse quark momenta and the Sudakov factors were considered. Unfortunately, direct GPDs extraction from observables is impossible. In our approach we parameterize GPDs using the DD form and known constraints on PDFs. The obtained results on meson production were compared with experiment.

It was shown that the k_\perp^2/Q^2 corrections in the propagators of the hard subprocess amplitude were essential in the description of the cross section at low Q^2 . They decrease σ by a factor of about 10 at $Q^2 \sim 3\text{GeV}^2$, and the cross section becomes close to experiment.

The H GPDs calculated using the CTEQ6 parameterization for gluon, sea and valence quarks were used to analyze vector meson production on the unpolarized target. Our

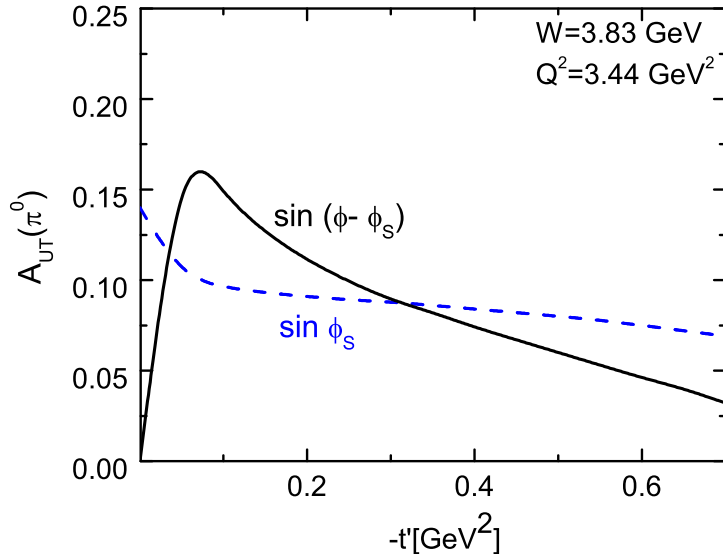


Figure 12: Results for the $\sin(\phi - \phi_s)$ and $\sin \phi_s$ moments of the transverse target asymmetries for π^0 electroproduction

results are in good agreement with the experiment from HERMES to HERA energies.

Information on GPDs E can be obtained from experiments with the transversely polarized target. These observables at energies $W \sim 5 - 10 \text{ GeV}$ are sensitive to the H and E GPDs for valence and sea quarks. We model the E GPDs using information on the Pauli form factors of the nucleon and sum rules. Using these results we predict the cross sections and A_{UT} asymmetries for various meson electroproduction [5]. The experimental data are available now only for the ρ^0 production and are described well. We predict not small A_{UT} asymmetry for the ω production which most probably may be studied at HERMES and COMPASS.

The production of pseudoscalar mesons are sensitive to \tilde{H} and \tilde{E} GPDs. It was shown that the pion pole and twist -3 effects in the $\mathcal{M}_{0-,++}$ amplitude determined by H_T contribution are very important in understanding the cross section and spin asymmetries in the π^+ production. We estimate transversity GPD H_T using the model [23]. The description of data on the π^+ production at HERMES is carried out. We can conclude that information on various GPDs discussed above should not be far from reality.

We examine the role of transversity GPDs E_T which contribute to the $\mathcal{M}_{0+,++}$ amplitude. It was shown that the effects of E_T GPD are essential in the π^0 production. At HERMES and COMPASS energies the twist-3 E_T effects produce a large σ_T cross section [11] which exceeds substantially the leading twist longitudinal cross section. We predict not small cross section and spin asymmetries for the π^0 production. We expect that this result will be tested in future π^0 production experiments and shed light on the role of transversity effects in these reactions.

We can conclude that the meson electroproduction is a good tool to probe various GPDs.

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